BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B69 04098

SUBJECT: Relationship Between Spacecraft Structural Capability and Ground Wind Constraints - ML Action Item 157 - Case 620

DATE: April 25, 1969

FROM: W. W. Hough

ABSTRACT

This memorandum reviews the iterative analytical and experimental steps used to predict spacecraft structural loads due to ground winds and establish the maximum ground-wind environment in which it is structurally safe to launch. In the case of AAP-2, the procedure is far from complete; the next step is the static test on the payload.

Internal loads analyses at MSFC and at McDonnell Douglas (MDAC) have produced different results, even though both analyses were based on the same set of wind-induced external loads. The MSFC results indicate that the AM/MDA interface does not have sufficient strength to pass the ultimate lift-off load conditions of the original static test criteria, which included a 28-knot ground wind. However, with a very minor structural change and a downward revision of the wind criteria to 24 knots, they are confident of a successful static test. MDAC believes the structure would have passed the test under the original criteria. The static test should determine which analysis is the more accurate. If the MDAC results are correct, MSFC should have no objection to raising the flight lift-off wind constraint back to 28 knots. Even if the MSFC results are not conservative, lower (than static test) weight and c.g. position of the MDA will decrease the actual lift-off loads and some relief of the 24-knot test constraint can be expected.

Since the disagreement between MSFC and MDAC on internal loads probably cannot be resolved without the static test, and since MSFC is unwilling to commit the structure to test conditions they feel will fail it, the use of the presently planned static test criteria (24-knot wind) is recommended.

The probability of the peak wind exceeding even 24 knots at the instant of lift-off is very low, but if it does, a short hold is not critical in the case of AAP-2 as there is no launch-on-time constraint dictated by rendezvous profiles. Therefore, no major structural mods seem warranted.

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ABSTRACT Continued

The approach of making the launch vs. hold decision based on measured loads rather than measured winds is definitely attractive, as it avoids the uncertainties (which are usually treated by conservatism) involved in translating wind speeds into loads. This Apollo Program technique should be continued for AAP launches.

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MEMORANDUM FOR FILE

Ground winds at the time of launch result in structural loads in a space vehicle. This memorandum reviews the experimental and analytical steps that are used to predict structural loads as a function of the wind, check space-vehicle strength against predicted loads, and establish the maximum ground-wind environment in which it is structurally safe to launch. The author hopes that this paper will serve as a short course for those unfamiliar with the subject, and has therefore included appropriate definitions and details at the expense of brevity.

The particular problem that led to this review is the possibility of a lower than usual lift-off wind constraint for AAP-2 due to a strength problem at the Airlock Module/Multiple Docking Adapter interface. The specifics of this problem are given; however, the procedure for determining wind constraints is iterative and, in the case of AAP-2, not yet complete.

SPECIFICATION OF THE WIND AND PROBABILITY OF OCCURRENCE

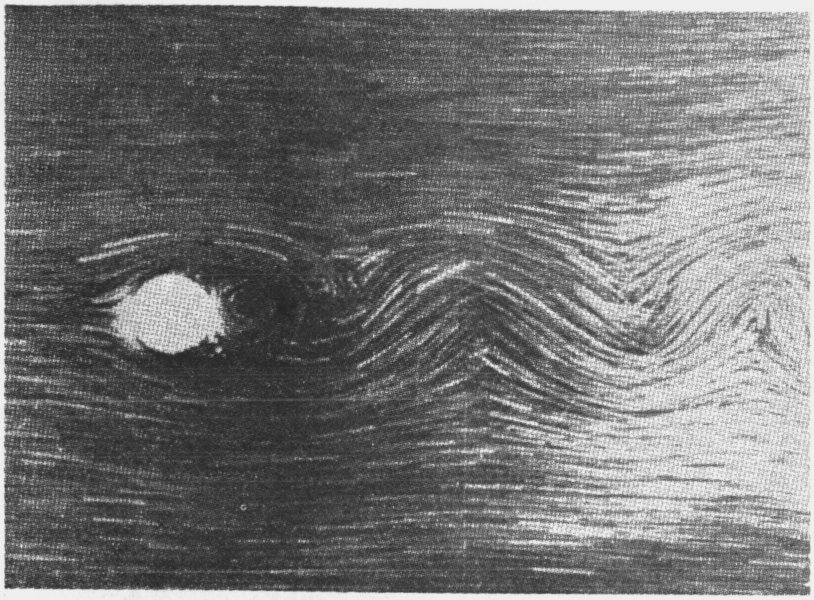
The Saturn IB vehicle with an Apollo payload (SA-205 Configuration) was structurally capable of lift-off in a 95 percentile ground wind. A 95 percentile wind is defined as that wind-speed profile (the speed increases with height above the ground) that, with a 95% probability, will not be exceeded during any one hour of the windiest month. Based on about 15 years of wind data taken at KSC, and with the profile referenced to the wind speed 60 feet above the ground (local sand level), which is an accepted standard, the 95 percentile peak wind at KSC is approximately 28 knots.

If a structures man says that he has a lift-off wind constraint of 28 knots, he means that his structure is capable of withstanding wind-induced loads (superimposed on other lift-off loads) when the wind speed 60 feet above ground is less than or equal to 28 knots. If you ask the KSC meteorologist what your chances of getting off under this constraint are, he'll have a difficult time answering you. The answer is not 95%; your chances are much better. The 95 percentile wind says the probability of not exceeding 28 knots at 60 feet during any hour of the worst month is 95%, not that he expects higher winds for 3 minutes of every hour during that month. Assuming that you will keep the vehicle buttoned up if a squall line or hurricane is coming up the coast, your chances of seeing a sudden gust that exceeds 28 knots at the instant of launch are almost negligible. To illustrate, of all the MSFC-built vehicles (not just Saturns) that have been launched, the highest winds at lift-off were measured on SA-205. The measured winds for this first manned Apollo mission were 18-19 knots, with peaks to 21 knots.

The fact that there is an exceedingly low probability of exceeding a 95 percentile wind at lift-off does not eliminate the constraint. The wind (or wind-induced loads) must be monitored during the final count, and if the constraint is exceeded, the launch must be held until the weather is calmer. On later AAP missions (not AAP-2) where rendezvous profiles require "launch-on-time," high winds for periods of minutes would not result in holds of order minutes, but of order days. AAP-2, however, does not have a launch-on-time constraint.

WIND-INDUCED LOADS PRIOR TO LIFT-OFF

When a free-standing vehicle, clamped at its base, is exposed to ground winds, it will bend as a cantilever beam in the direction of the wind. Its static deflection is proportional to the square of the wind speed. The bending moment increases from zero at the top to maximum at the base. The wind can also induce dynamic oscillations normal to the wind velocity. These oscillations are the result of von Karman vortex shedding. When the wind speed is high enough, very regular individual vortices form in parallel rows downwind on either side of the vehicle. Von Karman showed that vortices in one row must be symmetrically staggered with those of the other row for the arrangement to be stable, and determined the ratio of row separation to the separation of vortices in one of the rows (References 1 and 2). Figure 1 (from Reference 1) shows photographs of the von Karman vortex trail behind a cylinder in an experiment where the Reynolds number was 250. The flow is not steady, as the vortices are carried off by the source flow and new ones form alternately on either side of the vehicle. The frequency of the shedding is expressed approximately as $f = 0.22\ V/D$ when D is the diameter of the cylinder and V is the wind velocity. The periodic shedding of the vortices causes an oscillating lateral pressure distribution. When the frequency of the shedding (equivalently the frequency of the lateral pressure oscillation) coincides with the natural frequency of the cantilevered vehicle, violent elastic-body oscillations can occur.



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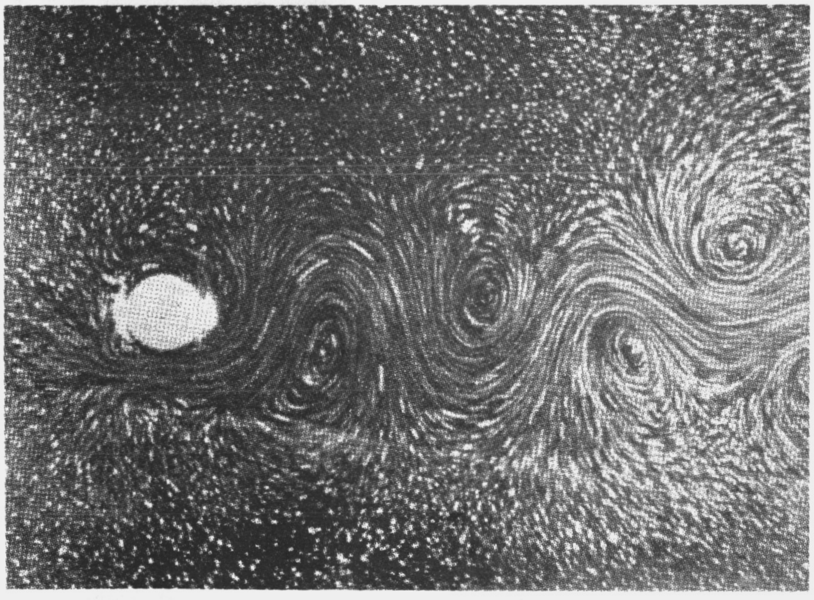

THE CAMERA IS AT REST WITH RESPECT TO THE SOURCE FLOW

FIGURE 1 - VON KARMAN VORTEX TRAIL
REYNOLDS NUMBER = 250

It is possible that the lateral motion of the vehicle can increase the pressure difference such that flutter occurs. Flutter is a dynamic instability, which can be described as forced oscillation with negative damping or positive feedback. Flutter of an unfueled Saturn V has been observed in scale model wind-tunnel tests, and has led to the addition of a mechanical damper to the ground support equipment. The damper connects the top of the spacecraft to the Launch Umbilical Tower or Mobile Service Structure, and provides positive damping in cases of forced oscillation due to vortex shedding. Flutter has not been observed for fueled Saturn V or Saturn IB configurations.

The basic source of predictions on wind-induced external loads are wind-tunnel tests using scale models of the vehicles. At MSFC, bending moment and deflection distributions along the cantilevered vehicle are generated by the Aero-Astrodynamics Laboratory. The static component parallel to the wind and the peak lateral component, which is due to vortex shedding, are determined as a function of wind speed. External loads based on wind-tunnel data can be refined by computer simulations, which incorporate accurate stiffness models and cantilever dynamic mode shapes.

There have been many questions raised about the ability to properly scale the vehicle and control the wind profile in a wind tunnel. Scaling problems are complicated by the presence of GSE, such as the Launch Umbilical Tower. The only (to the author's knowledge) full-scale investigations of wind-induced loads, including the vortex shedding phenomenon, were performed on a Jupiter launch vehicle by Langly Research Center at Wallops Island. MSFC claims their scale model test techniques gave results for the Jupiter which compared favorably with the full-scale results. Langley's wind-tunnel tests, however, gave results that predicted loads less than those actually observed.

Although dynamic oscillation of a Saturn vehicle due to vortex shedding has not been observed at KSC (every effort is is made to prevent the phenomenon), there have been failures in GSE that have to be attributed to vortex shedding. Tubular members in the Mobile Service Structure have failed at their ends, and an aerodynamic rather than structural fix is being installed. Figure 2, a photograph of a Thor missile at Wallops Island, is a graphic example of a wind-induced failure. No wind or load data were taken at the time of the failure, however.

Although the scale model technique of predicting loads in a cantilever vehicle lack an abundance of full-scale correlation, it is the best design tool available. In the case

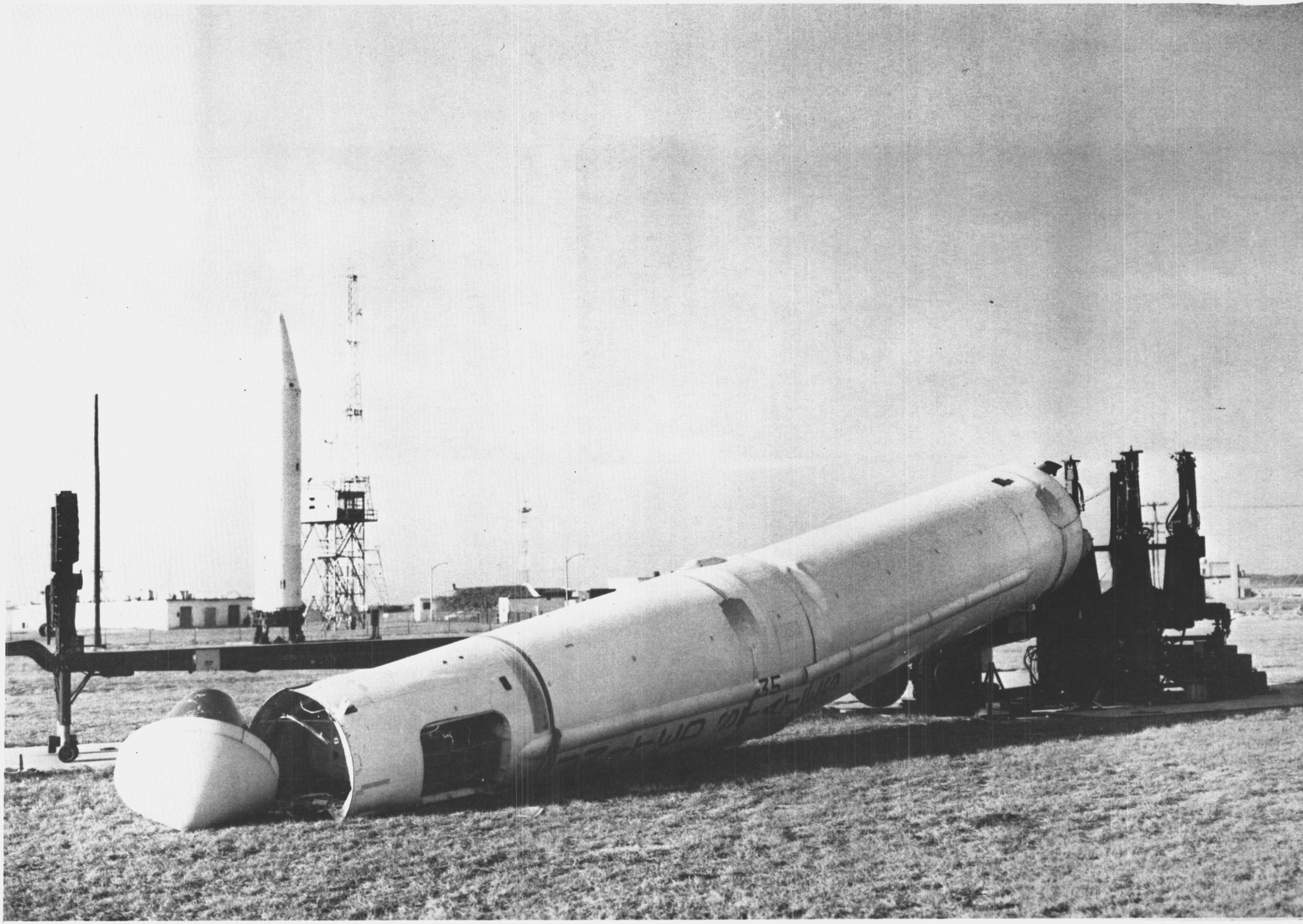

FIGURE 2 - WIND-INDUCED FAILURE OF THOR MISSILE

of AAP-2 with the Payload Shroud (PS), wind-tunnel tests have not yet been done. The external configuration is similar, however, to the SA-203 vehicle and to the old Saturn IB - Centaur concept, both of which have had wind-tunnel testing. The 203 shroud had no cylindrical section and the Saturn IB - Centaur shroud had a 260-inch diameter by 349-inch long cylindrical section. The PS has a 170-inch long cylindrical section. The conical sections of the nose cones are identical in the three cases, except for the tower jettison motor on the AAP-PS. The present bending moment distribution data for AAP-2 is based on an interpolation of the wind-tunnel data on the two earlier configurations as modified by analytical treatment of AAP-2 stiffness and modal data.

LIFT-OFF LOADS

At lift-off, the fixed-free (cantilevered) vehicle instantly becomes a free-free vehicle. When the hold-down arms release, the base bending moment, which was maximum in the cantilever condition, must instantly go to zero. The deflected shape must change so it is compatible with the new boundry conditions while maintaining the same strain (potential) plus kinetic energy (assuming no damping).

The strain energy due to bending is one half the integral over the length of the square of moment divided by the product of the modulus of elasticity times the moment of inertia of the cross section.

$$V = \frac{1}{2}\int_{o}^{l} \frac{M^2}{EI}\,dx$$

If we match the strain energy at maximum deflection (when the kinetic energy is zero) in the two cases, we can see that the bending moment high in the free-free vehicle has to increase over that in the fixed-free vehicle as a consequence of the base bending moment change from maximum to zero. This is commonly known as the "twang" effect.

The calculation of the bending moment distribution due to twang, and also lateral shear loads in the vehicle, is performed at MSFC by the Structures Division of P&VE. They use the static parallel components and the peak normal dynamic components of the bending moment distribution (or deflection distribution) in the cantilever vehicle, which have been furnished by Aero-Astrodynamics, as initial conditions in a standard elastic body lateral response program. For any wind speed profile (they usually start with the 95 percentile wind), the results of the program give time histories of the bending and shear loads along the vehicle, including the payload within the shroud.

The buildup of thrust, and the sudden release of the hold-down arms, causes axial load transients in the vehicle. Here, the thrust loads reacted by the hold-down structure are suddenly reacted by the mass of the vehicle. The time histories of the axial oscillations and loads along the vehicle are computed in another modal response program, and are superimposed on the shear and bending moment time histories. The output of the structural loads group is then a complete picture of expected axial load, lateral load (shear), and bending moment along the vehicle as a function of time. The total time between hold-down arm release and the observance of peak lift-off loads is on the order of a second.

At each critical vehicle station, the maximum expected bending moment, shear, and axial load can be picked from the time histories. The three components of the load are not necessarily at their maximums simultaneously, however. Therefore, the maximum of each is picked and listed along with the simultaneous values of the other two. These three sets of loads for each critical station become the limit load conditions. Limit load is defined as the maximum expected load that can actually occur during the flight phase, in this case lift-off.

In the case of AAP-2, the limit loads at lift-off were initially determined for a 95 percentile (28 knot) wind with an MDA weight of 10,000 pounds and c.g. at vehicle station 1981. This weight and c.g. were agreed to approximately a year ago as the conditions for the AM/MDA combined static test.

It must be noted that a change in weight, c.g., wind speed, or vehicle/payload stiffness requires a detailed re-evaluation of lift-off loads. The effect of any of these changes on loads cannot be determined by linear extrapolation. In the case of a change in wind speed (to the first order), the axial loads do not change, the initial conditions of bending moment and shear parallel to the wind are proportional to the square of the wind speed, and the bending moment and shear perpendicular to the wind are a function of the proximity of the vortex shedding frequency to the cantilever natural frequency of the vehicle.

INTERNAL LOADS ANALYSIS

The conversion of limit load conditions at critical vehicle or payload stations to stresses in individual components of the structure is termed internal loads analysis. Different analytical techniques can be employed, and they sometimes give different answers. This has been the case in AAP-2, where MSFC and McDonnell Douglas - Eastern Division (MDAC-ED) analyses have resulted in disagreement on the capability of the AM/MDA interface for static test conditions.

The MSFC internal loads analysis is done by Martin Marietta Corporation. A detailed elastic stiffness (or flexibility) model of the structure is generated by a computer. Applied forces are chosen to match the specified limit load condition at all critical stations in much the same manner as loading conditions for a static test are picked. The computer then generates the loads (or stresses) in each component of the structure due to those static forces. The technique is based on maintaining compatible elastic deformations of joints; the simplest example of this technique is the stress analysis of a statically indeterminate truss given in all texts on the theory of structures.

The MDAC-ED technique used to determine the stress distribution at the AM/MDA interface was not as complex as the MSFC/Martin technique. MDAC calculated the effective area of the interface structure and applied the limit loads specified by MSFC directly, assuming that the plane of the interface remained a plane.

The results of the MSFC internal loads analysis indicated that the loads (limit condition) that had to be carried through the joint between the AM interface ring and a T-section stringer (one of eight) on the Structural Transistion Section (STS) exceeded the ultimate strength capability of the joint. The MDAC-ED analysis indicated that the joint was not only good for limit load condition, but had an ultimate factor of safety (F.S.) of about 1.5. The ultimate factor of safety is defined as the ratio between the allowable ultimate load capability, as determined by strength, and the limit load. An ultimate factor of safety of 1.25 is a requirement for AM/MDA structure, and is a static test condition. That is, the static test article will be tested to 1.25 times expected limit loads. Another term used is margin of safety (M.S.), and is defined by MSFC as:

$$\text{M.S.} = \frac{\text{allowable ultimate load}}{\text{F.S.} \times \text{limit load}} - 1$$

By this definition, a structure designed to fail (not yield, but break or buckle) at F.S. times limit load has a M.S. of zero. MSFC's estimate of the M.S. of the STS joint in question with an ultimate F.S. of 1.25 was approximately - 25%. Working back through the definition of M.S., we see that MSFC expected the joint to fail at a load 6% less than limit. [(1-.25)(1.25) = allowable/limit = 0.94]

REVISION OF AAP-2 STATIC TEST CONDITIONS

The static test of the AM, MDA, and PS will serve not only as a verification test of the structure, but as a check on the analytical techniques. Simply stated, it will serve to determine who is closer to being right about internal loads. However, MSFC is not willing to commit the test articles to test conditions that they feel will fail it, as the AM will later be modified for dynamic testing and the MDA will become the 1-g trainer.

A major change to the interface structure which would give MSFC the confidence they want to proceed to static test with the stated lift-off conditions - namely, 10,000 lb MDA, c.g. at station 1981, F.S. = 1.25, 95 percentile wind (28 knots), and zero internal gage pressure - would force a fairly extensive re-analysis. Because of changed stiffnesses, limit loads and internal loads would have to be re-calculated. This, plus the physical modification of the structure, would probably delay the static test for several months. Changes in mass and/or c.g. location would cause similar delays. The simplest thing that could be done was for the strength people to determine the bending and shear limit load conditions (superimposed on unchanged axial limit conditions) that they could accept, and work backwards to determine the wind speed that gave these limit loads. This was done, and it was determined that at a 24-knot peak wind, the M.S. at the AM/MDA interface became - 3% as opposed to the - 25% at 28 knots. A simple change of 16 rivets which join the 8 STS T-section stringers to the interface ring would make the M.S. positive. MDAC-ED was therefore directed to change the 16 - 3/16" aluminum rivets to 1/4" aluminum rivets, and MSFC plans to proceed to the static test using a 24-knot wind criteria.

DETERMINATION OF APP-2 LIFT-OFF WIND CONSTRAINT

Simply because the static test will demonstrate the conservatism, or lack of it, in the analytical techniques, it will be a major step in establishing actual lift-off constraints. Certainly, one would expect a re-iteration of at least one of the analyses based on the static test so that equivalent results are obtained.

There are reasons to be optimistic that the 24-knot static-test wind criteria can be raised for flight. First, the loaded MDA weight is expected to be closer to 8300 pounds rather than 10,000 pounds, and the c.g. is expected to be about 10 inches lower than station 1981. Both of these differences will reduce interface loads for a given set of conditions, and the wind constraint can therefore be raised to the extent that it produces the same interface loads. Second, the MSFC elastic model technique for determining internal loads assumes that deformations at ultimate conditions are still elastic. Since the dynamic (twang) loads result from the conversion of kinetic energy into strain energy, and since in reality inelastic strain will occur before failure, more strain energy can actually be stored than that which is permitted by the analytical technique. The MSFC technique is conservative as it predicts higher stresses (above yield) than will actually occur for a particular energy storage requirement.

Based on what we know today, we can presume that the lift-off constraint will be higher than 24 knots. We can't say, however, that it will be 28 knots without a structural change. MSFC has investigated possible structural fixes which they believe would permit a 28-knot criteria, and the estimated weight increases are 60 pounds to the MDA and 32 pounds to the AM. There are, however, a couple of things we don't know today which might negate these presumptions. The first is the results of wind-tunnel tests on the Saturn IB with the Payload Shroud, including the tower jettison motor. Remember that external loads for this configuration were based on an interpolation between SA-203 and SaIB - Centaur data, and neither of these configurations had a jettison motor on top. Another possible concern might arise if the MSFC internal loads analyses technique proves to be accurate. The corrolary says the MDAC-ED technique is unconservative, and there might be other areas in the AM with insufficient strength capability. (The STS is the only AM area analyzed in detail by MSFC.) This possibility is admittedly difficult to reconcile with McDonnell's very successful history of building working machines.

WHAT WIND-CONSTRAINT?

In recent Saturn launches, there has been a structural wind constraint only as a backup to a redundant system of strain gages. Since there is so much uncertainty about the relationship between wind profile and external loads, and the loads are in reality the important parameter in the structural capability problem, it is far preferable to measure and place a constraint on the loads. MSC has established that there is a linear relationship between vehicle bending moment just prior to lift-off and peak spacecraft loads (due to twang) just after lift-off (Reference 3). The technique of monitoring existing strain gages in the vehicle rather than an anemometer 60 feet off the ground, and comparing the results with a load constraint rather than a wind speed constraint, has been used on all recent Saturn launches. This is not to say that the wind was not monitored - it was, but anemometer data would have been used for a "launch vs. hold" decision only if the strain gage system had failed.

The strain gages on the Saturn IB are located in eight places on the spider beam between the stages at station 942. Specifically, they measure the strain in each of eight studs that join the four S-IB stage LOX tanks to the beam. Any three gages are sufficient to determine bending moment magnitude and direction, so there is a great deal of redundancy among the gages themselves. Redundant readout capability is provided with instrumentation at both KSC and MSFC. The problem of calibrating the gages has been delt with in the past by an actual lateral "pull" test. A known lateral load was applied to the tops of the SA-204 and 205 vehicles, giving a known bending moment at station 942, and the strain in each of the eight studs measured. Another method, of calibration is to measure the strains before and after S-IVB stage LOX loading, although this is not as accurate simply because the strains produced are smaller. The repeatibility between the SA-204 and 205 pull tests was very good, and MSFC therefore prefers to work with a constraint on bending moment at station 942 rather than a wind constraint for lift-off, even if they are not permitted to calibrate the gages on the AAP vehicles. They would, however, prefer to do a pull test on each for strain gage calibration.

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

The relationship between space-vehicle structural capability and ground wind constraints at lift-off has been reviewed. So have the analytical and experimental steps used at MSFC to predict wind-induced loads and establish lift-off wind constraints. In the case of AAP-2, the iterative procedure for determining wind constraints is far from complete. The next step is the performance of the static test on the payload.

MSFC believes, based on their own internal loads analysis, that the AM/MDA interface does not have sufficient strength to pass the ultimate lift-off load conditions of the original static test criteria, which included a 28-knot ground wind. However, with a minor change in 16 rivets in the STS, and a revision of the wind criteria to 24 knots, they are confident of a successful static test, and have thus made these changes. MDAC-ED disagrees with the results of the MSFC internal loads analysis and believes the structure would have passed the test with a 28-knot wind criteria and without the rivet change. Presumably, the static test will determine which analysis is closer to being correct. If the MDAC results turn out to be right, MSFC should have no objection to raising the flight lift-off wind constraint back to 28 knots. Even if the MSFC results are not conservative, lower (than static test) weight and c.g. position of the MDA will decrease the actual lift-off loads and some relief in the 24-knot constraint can be expected.

If, after the results of the static test are available, re-iteration of the loads analyses for a flight-weight payload still dictate a wind-constraint less than 28 knots, a structural fix can be applied to the AM/MDA interface to aleviate the constraint. However, a weight penalty close to 100 pounds would be incurred. Since the probability of the peak wind exceeding even 24 knots at the instant of lift-off is very low, and because there is no launch-on-time constraint on AAP-2, the addition of 100 pounds in structural mods is certainly not warranted now, and probably won't be after the static test results are in.

Since the disagreement between MSFC and MDAC on internal loads probably cannot be resolved without the static test, and since MSFC is unwilling to commit the structure to test conditions they feel will fail it, the use of the presently planned static test criteria (24-knot wind) is recommended.

The approach of making the launch vs. hold decision based on measured loads rather than measured winds is definitely attractive, as it avoids the uncertainties (which are usually treated by conservatism) involved in translating wind speeds into loads. This Apollo Program technique should be continued for AAP launches.

ACKNOWLEDGEMENT

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William W. Hough

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REFERENCES

1) Tietjens, O. J., Applied Hydro-and Aeromechanics, based on the lectures of L. Prandtl, Engineering Societies Monographs, Dover Edition, Dover Publications, New York 1957.

2. Lamb, Sir Horace, Hydrodynamics, 6th Edition, Chapter 156, Dover Publications, New York, 1945.

3. Brubaker, W. C., "Spacecraft Launch Wind Constraint at Lift-off," Bellcomm Memorandum for File, March 7, 1968.